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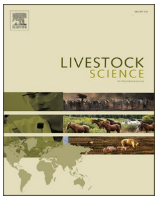

Local non-food yeast protein in pig production–environmental impacts and land use efficiency

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HIGHLIGHTS

- Yeast protein can be produced from wood sugar.
- Yeast protein replacing imported feed protein gives lower environmental impacts when utilised in pig production.
- Feed-food competition was avoided when using wood-based yeast protein in animal production.
- Pig production using a yeast-based diet was a net producer of human digestible protein.

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ABSTRACT

The aim of this study was to analyse the sustainability of pig production based on a diet containing yeast as a protein source. The yeast is produced from sugar, and the sugar can be produced from hydrolysed wood through a biorefinery process. This study included yeast from two different biorefinery processes: 1) a domestic demo plant in connection with a complex biorefinery, and 2) a small-scale wood refinery process largely based on wood residues. In the yeast diets, the yeast replaced soybean meal as a protein source and the two yeast diets were compared with a standard diet. The environmental impacts from the pig production systems were assessed by using life cycle assessment (LCA), and the functional unit was 1 kg carcass weight of pork at the farm gate.

The results from the study show that yeast replacing imported feed protein sources used in pig production gives a lower impact for biodiversity loss and climate change including land use change . The lower impact was created by the replacement of soybean meal with yeast from wood sugar in the feed recipe. Also, the scenarios with yeast diets gave a land use ratio below 1, indicating an improved land use efficiency regarding producing human digestible protein. Even though the forest land used for deriving wood sugar constitutes a greater area than the corresponding area for soybean meal production, the forest land does not occupy areas suitable for food production. The reference case, representing current pig production and feeding system, had a land use ratio of 1.15, meaning that the feed production was directly competing for the area suitable for food production.

The overall conclusion was that the utilisation of yeast from wood sugar appears to avoid feed-food competition and at the same time to be an environmentally sustainable solution for future feed protein employed in pig production.

1. Introduction

Global food producers are under pressure to reduce their environmental impact and change direction towards more sustainable production. Pig production is one of the most important livestock systems and globally pork accounts for approximately one third of total meat production (FAOSTAT, 2022). Feed production is the most significant contributor to environmental impacts in a pig production system (Bonesmo et al., 2012; Eriksson et al., 2005; Reckmann et al., 2013) and many countries, like Norway, has a high dependency on imported feed ingredients, such as soybean meal which traditionally is an important protein source in the pig diet. Several life cycle assessments (LCAs) have

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been carried out based on experiments investigating how different protein sources affect sustainability in pig production (McAuliffe et al., 2016; Meul et al., 2012; Stephen, 2012). Stephen (2012) found that a soy-based diet had a higher environmental impact per kg live weight of pig compared to a diet where the soy was replaced by peas, beans, and lupins grown in the UK. A Swedish LCA study of pig production shows that the results for climate change and energy use were comparatively lower when employing a diet with protein from locally grown peas and rapeseed cake rather than soybean meal, but the burdens were greater for the indicators eutrophication, acidification, and land use (Eriksson et al., 2005). There are, however, limited options for replacing soybean meal with alternative high-protein ingredients in compound diets for fattening pigs, without increasing the greenhouse gas emissions (de Boer et al., 2014). Soybean meal has a high nutritional value ensuring a high animal growth rate, which makes it difficult to find alternative high-quality protein sources. In recent years, efforts have been made to find new innovative methods of protein production, including insect meal and single-cell organisms such as yeast, as alternatives to soybean meal (Omar et al., 2012; Smetana et al., 2016; Van Huis et al., 2020; Øverland & Skrede, 2017).

Arable land is a limited resource and should be used for food production directly, but a major part is used for production of feed, and thus there is a feed-food competition related to the use of arable land (Mottet et al., 2017). Livestock production ought to a lesser extent to be based on feed resources grown in areas suitable for food production. A study of European feed production for pigs showed that the domestic production of cereals covered the energy demand, while protein-based ingredients such as soybean meal were largely imported, predominantly from South America (Sporchia et al., 2021). This is also the case in Norway, where less than 3.5 % of the total area is arable land (NIBIO, 2020). Owing to the limited practicability of cultivating feed crops, the development of novel feed ingredients provides a promising opportunity to increase the share of local protein sources. Recently, there has been a focus on developing sustainable feed sources from local renewable natural resources such as wood by-products (Lapeña et al., 2020; Øverland & Skrede, 2017) and cultivated seaweed (Øverland et al., 2019). Yeast produced from wood can serve as a protein source without competing with areas for food production. Growth performance experiments on pigs, using yeast, show that *Cyberlindnera jadinii* yeast can replace up to 40% of the traditional protein sources in piglet diets after weaning, while maintaining growth performance, improving the digestive function, and producing more robust piglets (Cruz et al., 2019; Håkenåsen et al., 2020).

Yeast can be produced from second-generation sugars derived from lignocellulose from spruce and pine trees. These grow in areas that are not suitable for food production and therefore provide a more sustainable utilisation of area and resources (Øverland & Skrede, 2017). This study aimed to use LCA and land use ratio to analyse the sustainability of pig production systems utilising yeast protein in the feed, and to compare this with a production system using a standard compound diet.

2. Material and method

The study included a constructed reference case of pig production using a standard diet with soybean meal as a protein source and two alternative scenarios with a diet containing yeast as a protein source. The yeast was produced from hydrolysed wood sugar, which can be produced in different biorefinery processes. This study assumed wood sugar from two different domestic sources; a complex biorefinery process producing Excello sugars from Borregaard's BALI process (BALI scenario) and a small-scale wood refinery process largely based on wood residues producing wood molasses from Glommen Technology (MOLASSES scenario), as described in section 2.1. The two yeast diets were assumed to have an equally balanced feed composition with a crude protein level and net energy content similar to the standard diet used in the reference case (see section 2.2), for both piglets and slaughter pigs, providing the same growth performance. Thus, differences in environmental impact would only be linked to the feed compositions, but to be able to address the feed-food competition, the whole system were included in all scenarios.

The LCA method was used for assessing the environmental impact of both the reference case and the scenarios (see section 2.3). In addition, the issue of feed-food competition was addressed using the land use ratio, which accounts for an area's suitability for food production, as described by van Zanten et al. (2016; see section 2.4). Technical details relating to the pig production, which were necessary for the LCA calculations, are shown in supplementary materials (Table S1-S5).

2.1. *Yeast production*

2.1.1. *Wood sugar*

The principal raw material in the yeast fermentation process is sugar, which can be derived from non-food biomass. In this specific study, wood is used. The main components of wood are cellulose, hemicellulose, lignin, and extractives. By use of thermo-chemical treatment and enzyme assisted hydrolysis, the hemicellulose and cellulose are converted to five- and six-carbon sugars. In a large-scale cellulose industry, the usual primary objective is to manufacture cellulose fibres of high quality, and the by-products, lignin and hemicellulose, have traditionally been used as fuel at the cellulose plant. The wood sugar refinery processes can utilise residual wood that does not meet the fibre length requirements for the cellulose and paper industry, e.g. sawdust. There exist different technologies for the production of wood-based sugar and in this study, two processes were included: BALI sugar (Borregaard Advanced Lignin) and wood molasses (Glommen Technology).

The BALI sugar was produced at Borregaard's BALI plant in Norway (Møller & Modahl, 2020). Sugar is here produced from wood chips and pulpwood in a lignocellulose process, which comprises a two-step, multiple output process. The output streams from the first step are lignin and an intermediate going to hydrolysis. The upstream burdens of this process were allocated between these two products based on the heat values of dry matter, which correlate with the products' economic values. The allocation factors were 57% for crude lignin and 43% for the intermediate output. The outputs of the second step are five- and six-carbon sugars and unhydrolyzed residue. The unhydrolyzed residue is incinerated and the heat from the combustion replaces the energy mix that is used to produce steam at the main Borregaard biorefinery.

For the wood molasses, data for a mix of residual wood chips and pulpwood from spruce and pine were used. The raw materials are boiled under high pressure, the hemicellulose is extracted and then the sugar in the form of molasses is separated. The co-products from the process are bioenergy and animal bedding material. There are products comparable to these on the market and economic allocation factors have been calculated (Table S5). To obtain five- and six-carbon sugars, molasses is hydrolysed through a thermal process, using the residual heat from the process.

Yeast produced from Norwegian spruce or pine trees sugars is currently not commercially available as a protein source in Norway, and thus neither the BALI process, the wood molasses process nor the yeast process is used in full-scale production. Since this analysis describes different scenarios, it was assumed that production takes place in Norway and the inventory was based on domestic test production conditions and technical calculations.

2.1.2. *Yeast fermentation*

The five- and six-carbon sugars from spruce are the primary components in the yeast fermentation process, but a nitrogen source is also required. The nitrogen source can be either inorganic or organic, an example being residual streams such as blood or offal from the slaughter industry. If inorganic nitrogen is used, additional chemicals and minerals are necessary for the process. In this study, data for ammonia from a steam reforming production process have been employed together with chemicals and minerals as specified in Møller & Modahl (2020). The production of yeast gives an emission of approximately 1 kg CO_2 per kg of yeast produced. The carbon content in the CO_2 emission of sugar is originally from the carbon uptake in the wood from air. According to IPCC (2013), the characterisation factor for uptake and emissions of biogenic CO_2 is zero and are thus not included in the calculation of climate change.

The surplus CO_2 from yeast production can however be considered as a co-product from the yeast protein process and be used in greenhouse production of vegetables, e.g. tomatoes. Greenhouses usually use CO_2 from the combustion of propane, which provides both CO_2 gas and heat, or they use liquid CO_2 in combination with other heat sources. The relative economic value of yeast and CO_2, respectively, can be used to allocate the upstream impacts between these two products and thereby reduce the impacts from the yeast protein. Based on the prices in the Norwegian market for CO_2 and various protein sources for animal feed (faba beans and soybean meal; Norwegian Agriculture Agency, 2022), up to 35% of the environmental impact can be allocated to CO_2. Such utilisation of CO_2 has been included in a sensitivity analysis, see section 2.5.

2.1.3. Feed formulation

In the reference case, both the piglets and the growing-finishing pigs were assumed to be fed a traditional soy-based diet (standard diet), as described in Table 1. In the two scenarios with yeast produced with two different sources of sugar, BALI scenario and MOLASSES scenario, the piglets were assumed to be fed a yeast-based diet where 40% of the protein was replaced with yeast ('yeast') and the growing-finishers diet was based on yeast together with locally produced rapeseed meal and faba beans ('yeast-local'). The other feed ingredients were adjusted to give a balanced nutrient content in the diet. The proportion of locally produced protein in the diet for piglets was 79% for the piglet standard diet and 95% for the piglet yeast diet. Similarly, in the growing-finishers diet, the share of protein from local feed resources was 57% in the finisher standard diet and 100% for the growing-finisher yeast-local diet, as soybean meal was fully replaced by yeast, faba beans, and rapeseed meal.

Table 1
Feed ingredients (given as g/kg) and their country of origin in diets for sows, piglets, and growing-finisher pigs. The non-commercial Norwegian standard diets for livestock production were from Felleskjøpet Fôrutvikling (2021).

Feed ingredients	Country of origin	Sow feed (g/kg)	Piglet feed(g/kg)		Growing-finishing feed (g/kg)	
			Standard	Yeast	Standard	Yeast-local
Wheat	Norway	-	627.8	593.5	-	
Barley	Norway	245.0	100.0	100.0	585.5	533.2
Oats	Norway	400.0	50.0	50.0	150.0	150.0
Soybean meal	80% Brasil 20% Canada	40.0	80.0	19.2	142.6	-
Potato protein concentrate	West Europe	-	33.8	9.1	-	-
Fish meal	Norway	28.0	20.0	4.8	-	-
Rapeseed meal	Norway	108.0	20.0	4.9	60.0	93.4
Yeast	Norway	-	-	146.0	-	100.0
Faba beans	Norway	-	-	-	-	70.7
Rapeseed oil	Norway	-	19.7	23.4	-	-
Rendered fat	Norway	28.0	-	-	23.0	16.5
Molasses	West Europe	23.0	-	-	10.0	10.0
Beet pulp	West Europe	48.0	-	-	-	-
Wheat bran	Norway	17.0	-	-	-	-
Minerals, vitamins and amino acids	West Europe	63.0	48.7	49.1	28.9	26.2

Sow feed: Crude protein 150 g/kg, 9.5 MJ Net energy/kg
Piglet feed: Crude protein 174 g/kg, Net energy 9.9 MJ/kg,
Growing-finishing feed: Crude protein 155 g/kg, Net energy 9,4 MJ/kg.

On average, 80% of the soybean meal used in animal feed production in Norway is grown in Brazil, with the rest from Canada (Denofa, pers. comm. 2021). Data for soybeans from Brazil was modelled for specific states using the ecoinvent database (Wernet et al., 2016) and the composition was based on each state's share of production (ProTerra Foundation, 2019). Economic allocation was employed for soybean meal and soybean oil, using international prices for 2018/19 (FAO, 2020). Overseas shipping is included in the calculations.

For the production of domestic feed ingredients, Norwegian inventory data was used for barley, oats, wheat (Korsaeth et al., 2012; Statistics Norway, 2022), and faba beans (Korsaeth & Roer, 2016). The field production data regarding rapeseed was from Svanes et al. (2020) and the inventory for processing of rapeseed was data from Agri-footprint (Blonk Consultants, 2017) which was adapted for Norwegian conditions. The processing of rapeseed was a multi-output process that delivers the co-products of rapeseed oil and rapeseed meal, and economic allocation was applied. Rapeseeds were first crushed to remove the oil, yielding rapeseed cake as the first by-product. This was further processed through solvent extraction to yield the rapeseed meal.

Data for rendered fat was based on Norwegian site-specific data, using economic allocation between rendered fat and meat bone meal. The processing and allocation factors for molasses and beet pulp from sugar beets were from Zeist et al. (2012) and background data from ecoinvent (Wernet et al., 2016). Data for the remaining feed ingredients were from ecoinvent (limestone, sodium chloride, selenium, and iron, all of which were included in minerals, vitamins, and amino acids), Agri-footprint (fish meal, potato protein concentrate (Blonk Consultants, 2017)) and Agribalyse (monocalcium phosphate in minerals, vitamins, and amino acids (Koch & Salou, 2016)).

Domestic transport distances were calculated as a weighted average and collected from the feed industry. The domestic transport of feed ingredients was 129 km, calculated as a weighted average distance from grain production areas to the feed factory. For imported feed ingredients, the domestic transport distance was 125 km, based on the distance from the nearest port to the feed factory. The transport of the feed from the feed factory to the pig farm was assumed to be 100 km.

2.2. LCA method

2.2.1. Functional unit

The functional unit was 1 kg carcass weight of pork at the farm gate. Carcass weight was selected as the functional unit as this better represents the product's functionality and was easier to convert to meat products than final live weight. The system boundaries were from cradle to farm gate. See section 2.3.2 for more details. The LCA was attributional and carried out in accordance with ISO 14040/14044 (ISO, 2006a; 2006b) and follows the modelling principles in PEFCR for feed production (FEFAC, 2018).

2.2.2. System boundaries

Fig. 1 shows the system boundaries for the LCA of the pig production system. It was assumed that the gilt - sow - piglet system existed at a breeding farm and that the growing of weaned piglets and finishers took place at a slaughter pig production farm. Fertiliser for grain production was included in the data for grains and emissions from the application of manure were therefore excluded to avoid double counting.

2.2.3. Allocation

Allocation was avoided by subdividing the processes where possible. Avoided burdens have also been used where relevant. Still, there were

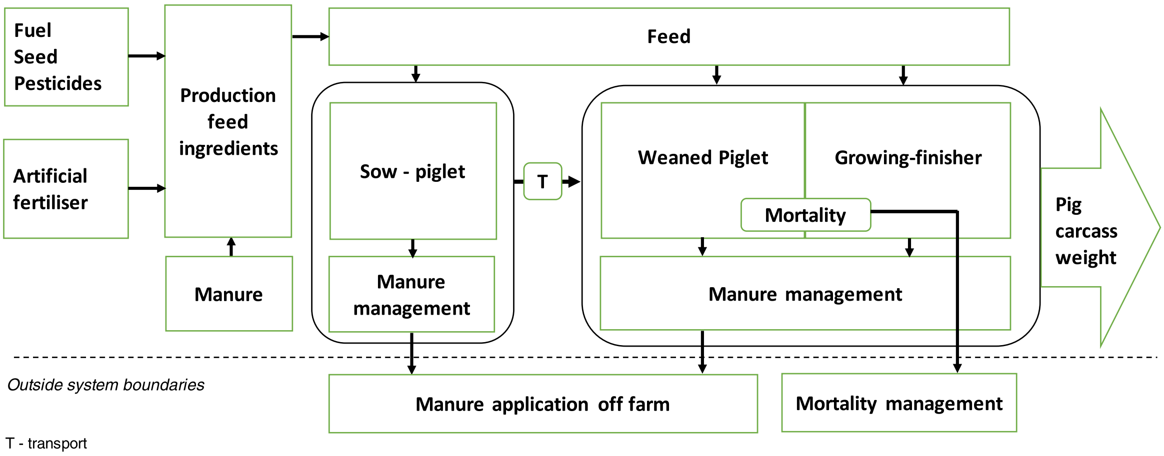

Fig. 1. General system description for the pig production system. The sow - piglet system took place at a breeding farm and the weaned piglets were transported to a slaughter pig production farm.

several multiple output processes in the studied system, where allocation was the most feasible solution, such as feed ingredients and manure. Economic allocation was applied to distribute the impacts of co-products from wood sugar processing and from crops at the farm, in accordance with PEFCR for feed (FEFAC, 2018). In the sensitivity analysis for both scenarios, the surplus CO_2 from the yeast fermentation process was utilised in greenhouse production and the impacts were allocated using economic allocation factors, see section 2.1.2. Manure was by default considered as residue (no economic value) with no upstream burden allocated (FAO, 2019). The guidelines in the FAO report were followed as important methodological input for the development of PEFCR for feed. For the calculation of carcass weight from final live weight, all environmental impacts were allocated to carcass weight, which means that no allocation has been made to by-products at the slaughterhouse.

2.2.4. *Impact categories*

Greenhouse gas emissions are one of several significant environmental impacts, and it is important to ensure that actions taken to reduce greenhouse gas emissions from food production do not produce a burden-shifting by increasing other environmental impacts, such as biodiversity and eutrophication. According to Rockström et al. (2009), the planetary boundaries have already been exceeded when it comes to biodiversity loss, eutrophication (Nitrogen-cycle), and climate change, and livestock production contributes significantly to these impact categories (FEFAC, 2018; van Hal et al., 2019). This is the reason for choosing these impact categories for this study.

For climate change, a time horizon of 100 years was applied and expressed as CO_2 equivalents (eq.) (IPCC, 2013 GWP 100a v1.03) and the results for climate change were reported with and without land use change (LUC). Soil carbon storage was not included in climate change as the feed production was not linked to a specific area with the necessary data for soil type, precipitation, and temperature. Impacts from eutrophication were calculated as emissions of all phosphate and nitrogen compounds converted to kg $PO4^{-3}$ eq (CML-IA baseline v3.06).

The impacts on biodiversity were estimated employing the method given by Chaudhary & Brooks (2018a). This biodiversity method provides characterisation factors for species loss which are calculated as a function of the ratio of species richness between each land use and reference state. In this study, the land occupation characterisation factors per ecoregion were applied, using the aggregated characterisation factor for the five taxonomic groups: mammals, birds, amphibians, reptiles, and plants. The reference was a natural habitat. Country of origin (Table 1) was used to place the cultivation of feed ingredients within an ecoregion. This was achieved by finding the respective areas on maps showing ecoregions (DMEER, 2021; Olson et al., 2001). Norway is an elongated country and comprises four ecoregions and the distribution of cultivated land and productive forest for each ecoregion is shown in Table 2. Characterisation factors were selected for each relevant ecoregion (Chaudhary & Brooks, 2018b). The land use categories were i) cropland, intense use for feed ingredients; ii) managed woods, intense use (clear-cut) for the spruce and pine for yeast production; iii) urban area, light use for the infrastructure in the background system. For managed woods, it would have been more appropriate to use the management type “light use, selectively logged forests”, however, no characterisation factors were available. The results were expressed as potential species loss showing the median values and the uncertainty range by use of the 2.5% and 97.5% percentile.

2.3. *Land Use ratio*

To assess the feed-food competition, the indicator land use ratio (LUR; van Zanten et al., 2016) was applied in the study:

$$\mathrm{LUR} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{m}\left(\mathrm{LO_{ij}x\ HDP\ m^{-2}\ y_j^{-1}}\right)}{\mathrm{HDP\ of\ 1\ kg\ ASF}}$$

where LO_{ij} is the land area (m^2) occupied for a year (y) to cultivate the amount of feed ingredient i (i=1,n) in country j (j=1,m) that is needed to produce 1 kg of animal-source food (ASF), including breeding and rearing of young stock, and HDP_j is the maximum amount of human-digestible protein (HDP) that can be produced per m^2 within a year by direct cultivation of food crops in country j. The denominator is the amount of HDP from the ASF produced on the same land area as in the numerator. The land use ratio is dimensionless since the numerator and the denominator have the same units.

The land area occupied was calculated by quantifying the land area required to cultivate feed ingredients per functional unit, and then determining the suitability of the occupied land to directly cultivate human food crops. For Norway, the suitability was assessed by using the area barometer (NIBIO, 2020) which specifies the area suitable or marginally suitable for food grain production, and correspondingly for

Table 2
Ecoregions in Norway and distribution of cultivated land and productive forest.

Norwegian ecoregions	Cultivated area (%)	Productive forest (%)
Scandinavian coastal conifer forests	21 %	9 %
Scandinavian and Russian taiga	69 %	67 %
Sarmatic mixed forests	4 %	9 %
Scandinavian Montane Birch forest and grasslands	6 %	15 %

feed grain production. The share of the Norwegian cropland area suitable or marginally suitable for food grain production is 22%. The forest land occupied for yeast production was not considered suitable for food production. For other countries in which the feed ingredients were produced, it was assumed that all the areas were suitable for direct food production. The human-digestible protein in the numerator was calculated using the country-average yield (FAOSTAT, 2022) from all land suitable for crop production, as well as the dry matter content, digestibility, and crude protein content for the protein crop with the highest HDP yield (van Zanten et al., 2016).

Data from the annual pig production statistics (Animalia, 2018) were used for the calculation of the human-digestible protein from the pork produced (ASF) in the denominator. The human-digestible protein of 1 kg carcass pork was calculated using the average protein content of pork (186 g protein per kg of raw meat), converted from boneless pork to carcass (850 g boneless pork per kg carcass). The human digestibility of pork was assumed to be equal to beef as listed in the paper by van Zanten et al. (2016).

2.4. *Sensitivity and uncertainty analysis*

To test the robustness of the results, climate change were presented both with and without LUC (Table 3). A sensitivity analysis was conducted regarding the CO_2 emissions from the yeast fermentation process, where the surplus biological CO_2 from sugar was utilised in greenhouse production. The economic value of the avoided CO_2 was used for calculating an allocation factor, see further description in section 2.1.2.

The results were presented as the mean value, including results for the 2.5% and 97.5% confidence interval (Table 3). The uncertainty was calculated using the Monte Carlo analysis in SimaPro. Standard deviations were used on data from the pig reporting system (Ingris) and the uncertainty in background data from the databases. For biodiversity, separate characterisation factors for 2.5% and 97.5% percentile were applied in calculating the uncertainty.

3. Results

The contribution made by different life cycle stages of the modelled pig production system to selected environmental impact categories for the reference case is shown in Fig. 2. The life cycle impacts have been shown for the following stages: feed production for sow and gilt, piglet and finisher; and corresponding splitting into animal groups for emissions from housing and manure storage, which also include emissions from enteric fermentation. The figure illustrates the fact that feed production constitutes a significant proportion of the environmental impacts, 64% of climate change excluding LUC and eutrophication, 70% of climate change and 100% of the land occupation and biodiversity loss. As additional information, the impact results for yeast are reported in Table S6.

Table 3 provides the results and the uncertainty range of the environmental impact and land use for the reference case and the two scenarios with yeast diet. The most noticeable difference was found in the land use ratio, where the yeast scenarios BALI and MOLASSES had a ratio 44% lower than the reference case. The second greatest difference was seen in biodiversity loss, where the yeast scenarios showed a lower impact than the reference case, with the BALI scenario being the lowest. There was also a clear difference between the reference case and the yeast scenarios for climate change including LUC. For climate change excluding LUC, however, there was no significant difference. For eutrophication, there were only minor dissimilarities between the reference case and the scenarios.

For the potential loss of biodiversity, using characterisation factors for aggregated taxa, the median values indicate a difference between the reference case and the two yeast scenarios, BALI and MOLASSES (Fig. 3). Nevertheless, when using the 2.5% and 97.5% percentile, the uncertainty ranges in the reference case overlap with those in the scenarios. A major part of the biodiversity loss in all three cases was linked to cropland in Norway, as over 80% of the weight of the feed comes from domestic production. Despite this, the reference case has the highest total species loss, and approximately 50% of the potential species loss was associated with the area for soybean production in Brazil. There was only minor biodiversity loss connected to soybean meal from Canada or the production of feed ingredients from Western Europe and urban areas used for infrastructure. This is in line with the fact that the feed ingredients that are grown in these regions also constitute a small part of the feed composition measured by weight. For the two yeast scenarios (BALI and MOLASSES), only a small share was linked to cropland in Brazil, since soybean meal was only included in the sow and gilt feed and a lower proportion in the piglet yeast feed. The second-largest share in

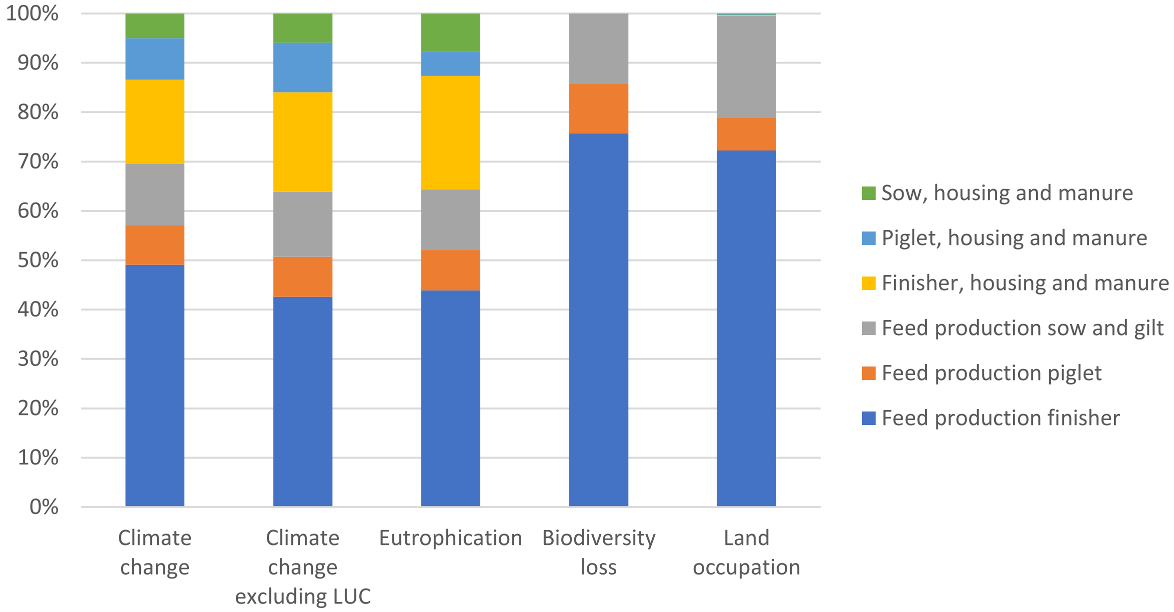

Fig. 2. Contribution analysis for the impact categories climate change, climate change excluding LUC, eutrophication, biodiversity loss and land occupation in the reference case with standard feed.

Table 3
Life cycle assessment (LCA) results for the pig production systems per kg carcass weight, with standard diet (reference case) and the two scenarios with a yeast diet, based on two differently produced sugars (BALI and MOLASSES) and given as mean value for each category with the confidence interval in cursive below.

	LCA impact method	Unit	Pig production system		
			Reference case	BALIscenario	MOLASSES scenario
Climate change (including LUC)	Baseline model of 100 years (IPCC, 2013)	kg CO_2 eq.	3.7 *3.64-3.85*	3.4 *3.32-3.50*	3.2 *3.13-3.31*
Climate change excluding LUC	As above, but subtracting CO_2 emissions from LUC	kg CO_2 eq.	3.15 *3.10-3.21*	3.3 *3.61-3.81*	3.1 *3.42-3.63*
Eutrophication	CML-IA baseline v3.06	kg PO_4^{---} eq.	0.015 *0.0143-0.0162*	0.014 *0.0138-0.0154*	0.014 *0.0129-0.0146*
Biodiversity loss	Product Biodiversity Footprints (Chaudhary & Brooks, 2018a)	Potential species loss	1.7E-13 *1.3E-13 - 2.2E-13*	1.1E-13 *8.5E-14-1.5E-13*	1.3E-13 *1.0E-13-1.7E-13*
Land occupation	Inventory results	m^2	8.25 *7.7-8.9*	9.65 *9.2-10.2*	11.1 *9.3-13.6*
Land use ratio	van Zanten et al. (2016)	Dimension-less	1.15	0.64	0.64

the yeast scenarios was linked to forest land in Norway, owing to the production of wood sugar for yeast production. The actual land occupation in square meters was largest for the two yeast scenarios compared to the reference case, with the highest value being for the MOLASSES scenario (see Table 3 and the secondary y-axis in Fig. 3).

The sensitivity analysis of allocating 35% of the impact of yeast and the upstream processes to CO_2 utilised in greenhouse production, gives a reduction in the impact for pig production for the yeast-scenarios (Table 4). The greatest reduction is for land occupation and biodiversity loss. The allocation gave only a minor reduction for climate change and eutrophication and no change for land use ratio.

4. Discussion

Feed production constitutes a significant proportion of the environmental impacts in pig production, especially for climate change and land use, and these findings were in line with other studies (Balkema et al., 2015; Eriksson et al., 2005; Johansen & Hjelkrem, 2018; Nguyen et al., 2011). However, differences in specific, calculated values of environmental impact will occur with differences in e.g. model specifications, system boundaries, characterisation factors, and proportion of soy in feed, such as with Bonesmo & Enger (2021), which has significantly lower climate change numbers per carcass weight. To achieve a reduction in the environmental impact from pig production it is important to focus on the feed ingredients and the composition of the diet. The two yeast scenarios, based on either BALI sugar or wood molasses for the production of yeast, represent the potential for using yeast produced from wood as an alternative to reduce the need for imported feed ingredients in diets for pigs. The results from the study show that the two scenarios with yeast diet give favourable results regarding land use ratio, biodiversity, and climate change including land use change (LUC) when compared with the reference case with a standard diet. Climate change excluding LUC shows no significant difference between the systems. This shows that the method and choice of data for calculating LUC were decisive for the results. This implies that pig production based on a diet containing yeast protein will only give lower greenhouse gas emissions if it is compared with soybean meal from areas where LUC have been calculated.

Variability in methods and data can significantly affect the LCA results of feed ingredients. Meul et al. (2012) found that the method chosen to account for LUC has a major impact when assessing the impact of different diets on climate change. Thus, calculation of LUC is one of the areas where special focus is required (van Middelaar et al., 2013). There is a broad agreement that LUC should be included in LCA, in accordance with LCA guidelines (European Commission Joint Research Centre, 2010; FAO, 2019; FEFAC, 2018). At the same time, a discussion is needed about the basis for the calculation of LUC in connection with the cultivation of soy. Although suppliers work with traceability of soy production to be able to document that the areas have not been deforested during the last 20 years, following the IPCC requirement (IPCC, 2006), a national average for calculation of LUC is still often used in LCA studies. Indirect land use changes (iLUC) is an aspect in consequential modelling (European Commission Joint Research Centre, 2010) and according to guidelines, there is no agreement on the calculation method and it should therefore not be included in attributional modelling. The principle for iLUC can, however, be employed as an argument for using national average data for LUC. iLUC refers to the situation that an additional demand for soy results in a transformation of hitherto unused land such as nature and fallow, to produce the displaced crop. The use of a national average can be justified, as the livestock production generates demand for soy and thus puts pressure on the relevant land areas. Since the sensitivity analysis showed that LUC was decisive for the results for climate change within this study, the magnitude of the values used for LUC also determines how much benefit will be gained by using feed based on domestically grown protein ingredients rather than soybean meal; in other words the difference in climate change between the systems using standard diet and the yeast diet.

The characterisation factors in the biodiversity method by Chaudhary & Brooks (2018a) are designed so that high biodiversity in an area gives a greater potential loss when the area has other uses than the natural state. The potential species loss is a potential value and is not linked to the possibility of reconverted to natural habitat. The reference case showed the highest total biodiversity loss, with almost 50% of potential species loss being associated with Brazil, owing to the area used for soybean production. This applies even though soy only makes up between 8-15 weight % of the standard diet. It was also because, according to the biodiversity method used, the characterisation factor for biodiversity loss for Brazil is very high. The Cerrado area is one of the richest of all tropical savanna regions and hosts a significant number of endemic species. The potential loss of species as a result of giving over these areas to agriculture was therefore high, compared with areas where biodiversity was originally lower.

The biodiversity method developed by Chaudhary & Brooks (2018a) was selected, because to date, it appears to be the best method for meeting the most important criteria for quantifying biodiversity in LCA. These criteria are a globally applicable method and with associated characterisation factors that include production intensity and relate to a reference condition, as proposed by Gabel et al. (2016). The previous version (Chaudhary et al., 2015) was recommended by UNEP/SETAC (2016) after a review process, and in this newer version (Chaudhary & Brooks, 2018a), the method has been updated in areas suggested by the UNEP/SETAC guidance. The method still has, however, a major potential for further development. Internationally, important work is underway to further develop both existing and new methods for the assessment of biodiversity in LCA. This will provide valuable input to LCA studies in the future, and, in particular, for food systems, since by seizing land they have a marked effect on biodiversity. Nevertheless, the biodiversity method does not include the direct impact on biodiversity associated with emissions from the system, such as the use of pesticides. When interpreting the results, therefore, it is important to be aware of the method's limitations. In this study, the focus was on the production of feed ingredients in different areas and origins, and as such, the method fits well with the goal and scope of the study. Therefore, although the method is uncertain, it still provides a good indication of the differences between the reference case and the scenarios.

The results for the land use ratio show a substantial difference between the reference case and the two alternative scenarios. The principal difference was due to the replacement of the soybean meal in the standard diet with yeast from wood sugar in the scenarios. In the scenarios, therefore, forest land was used instead of cropland suitable for human-edible food production. Even though forest land constitutes a larger area than the area used for soybean meal production, the forest area does not occupy potential resources for direct food production. A land use ratio of less than 1 implies that animals produce more human digestible protein per square metre than crops would have done (van Zanten et al., 2016). The reference case, representing today's pig production and feeding system, has a land use ratio of 1.15, showing that the feed used in the pig production was directly competing for area suitable for food production. The two scenarios, however, have a land use ratio of less than 1, and therefore produce more human digestible protein than would have been the case by producing food directly on the occupied areas. The scenarios thus reveal how pig production can become a net producer of protein. It can therefore be seen that, together with the lower or unchanged impacts on climate change and loss of biodiversity, the use of yeast from wood sugar appears to be an environmentally sustainable solution for the future with higher land use efficiency.

There is a major potential for the utilisation of by-products and side streams to a far greater extent than is the case today (Van Zanten et al., 2019). Research on the production of feed or food resources from non-human edible biomass shows promising results, although there is still a need to optimise the production of yeast and wood molasses and the raw materials included in the process. There are several options for

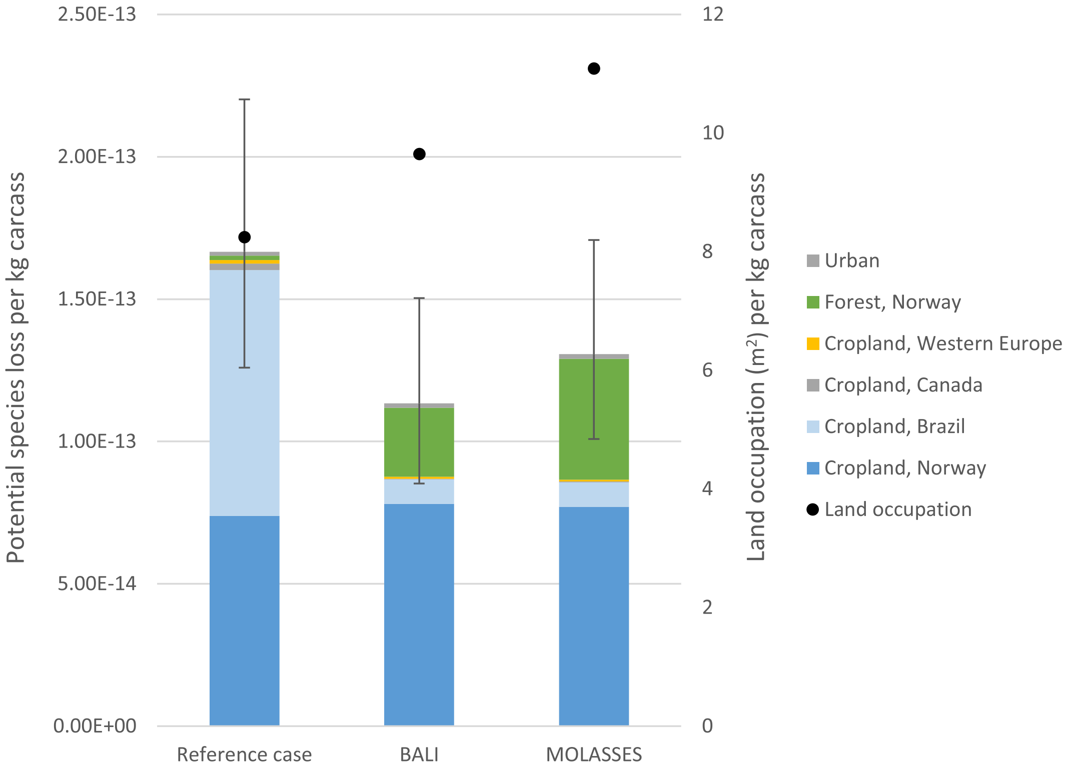

Fig. 3. Biodiversity expressed as the potential species loss per kg of carcass weight within land occupation type and country, showing median values and uncertainty range for 2,5% and 97,5% percentile. The characterisation factors used were for aggregated taxa and land occupation. Land occupation (m^2) is shown on the secondary y-axis.

Table 4
Results for the BALI and the MOLASSES scenarios and the corresponding sensitivity analysis relative to the reference case (given as 100%) for six impact categories. The sensitivity analysis shows the effect of allocating 35% of the upstream impacts from yeast production to the surplus CO_2 emissions used in greenhouse production.

	Reference case	BALI scenario	BALI sensitivity	MOLASSES scenario	MOLASSES sensitivity
Climate change	100 %	91 %	87 %	86 %	84 %
Climate change excluding LUC	100 %	106 %	101 %	100 %	98 %
Eutrophication	100 %	93 %	90 %	86 %	86 %
Biodiversity loss	100 %	68 %	63 %	78 %	70 %
Land occupation	100%	117%	108%	134%	120%
Land use ratio	100 %	56 %	56 %	55 %	55 %

increased circularity in the production of yeast from wood sugar. One of these is to utilise the excess CO_2 from the fermentation process in greenhouse production, and thus give a further reduction in the loss of biodiversity when compared with the reference case.

It will, however, not affect the land use ratio because the area suitable for direct food production is unchanged, and allocation only affects the forest land. Two other improvement options are the production of wood sugar from wood residuals and the use of alternative nitrogen sources such as offal in the fermentation of yeast. These options are not included in the study. In the future, the yeast (or other single-cell organisms) might be produced solely on waste streams or low-value resources contributing to a circular food system. The yeast scenarios have not only replaced soybean meal with yeast but also included other domestic feed ingredients such as faba beans and an increased amount of rapeseed meal. Although Norway has a limited area of arable land, there are opportunities to increase utilisation of resources through the growing of protein crops (Svanes et al., 2020) and in particular nitrogen-fixing crops which will reduce the need for nitrogen fertilisation (Priyadarshini et al., 2021). The scenarios in this study, therefore, provide a realistic alternative to the current feed ingredients in use. If not competing with human-edible crops, the use of a larger proportion of domestically produced feed ingredients will also promote a more circular food system.

It was assumed that the growth performance of pigs was similar with all the diets, since the diets were formulated to meet the nutritional requirement of the pigs with balanced digestible protein, amino acid and net energy levels. A potential adverse effect on performance could be related to the functional components in the yeast, which serve as an immunostimulant. A pro-inflammatory stimuli over time may lead to repartitioning of nutrient and energy from growth towards the immune system, thus leading to reduced growth performance. On the other hand the functional components in the yeast may have positive effect on pig’s health such as improved gut function and a reduced incidence of post-weaning diarrhoea (Cruz et al., 2019; Håkenåsen et al., 2020) and consequently growth performance is increased. In addition, Iakhno et al. (2021) found that piglets fed on yeast (40% of the crude protein) developed a more diverse faecal microbiome compared with piglets fed with soybean meal. The same study also indicated a carry-over effect on the faecal microbiome in the growing-finishing period, in pigs that had received a yeast-based diet in the weanling period. Diarrhoea is a major cause of morbidity and mortality in piglets (Wittig & Fabricius, 1992) and apart from disease-causing biogenic factors, the feed could also play an important role for individual gut health and illness. Soybean meal is known to have an inflammatory effect on the gut affecting digestive and nutrient absorption (Chikwati et al., 2013). In salmonids, enteritis induced by soybean meal is a well-described gut pathology, and examples are found in several studies (Baeverfjord & Krogdahl, 1996; Djordjevic et al., 2021; Urán et al., 2008), whereas both rapeseed meal (Onarman Umu et al., 2018; Pérez de Nanclares et al., 2017) and yeast (Agboola et al., 2021; Grammes et al., 2013) have shown favourable, prebiotic traits. There are also other current additives to feed that can improve growth performance, such as the addition of clay minerals which in trials have shown a significant decrease in feed intake and thus a reduction in environmental impacts (Anestis et al., 2020). Correspondingly, improved animal health can reduce greenhouse gas (GHG) emissions intensity in livestock systems while increasing productivity (Kipling et al., 2021). In other studies, it is found that weaning diarrhoea in piglets can both prolong the rearing period by eight days and increase mortality (Wallgren et al., 2012), and might therefore increase the environmental impact in practical pig production by 6% in the affected herds (Landquist et al., 2020). Further studies should explore the effect of feeding yeast to piglets under practical conditions, to improve the inclusion level of health and welfare in future sustainability analyses.

5. Conclusions

The study explored the possibilities of using wood-based yeast, produced from either BALI sugar or wood molasses, as a source of protein in comparison with a standard diet with soybean meal. Feed production constitutes a substantial proportion of the environmental impacts in pig production, and the introduction of yeast as a protein source was especially important for loss of biodiversity and climate change, as well as land use efficiency. The pig production systems using yeast-based diet for piglets and growing-finishing pigs have a land use ratio of less than 1, showing that pig production on yeast-based diets was a net producer of human digestible protein. There is still a need to optimise the production of yeast and wood molasses and the raw materials included in the process. In addition, there are opportunities for increasing the circularity by using wood residuals for production of wood sugar; use alternative nitrogen sources such as slaughter by-products to ferment yeast; and utilisation of the excess CO_2 from the fermentation process in other crop or vegetable production, such as greenhouse production. Altogether, using yeast from wood sugar in diets for pigs can be an environmentally sustainable solution for the future.

CRediT authorship contribution statement

Hanne Møller: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Stine Samsonstuen:** Validation, Writing – review & editing. **Margareth Øverland:** Supervision, Writing – review & editing, Funding acquisition. **Ingunn Saur Modahl:** Formal analysis, Writing – review & editing. **Hanne Fjerdingby Olsen:** Conceptualization, Writing – review & editing, Project administration, Supervision, Funding acquisition.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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